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Development of a Ground Multi-Mission Low-Cost Optical Terminal (LCOT) for Free-Space Optical Communications

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Abstract

Once confined to the realm of laboratory experiments and theoretical papers, space-based laser communications (lasercomm) are on the verge of achieving mainstream status. Organizations from Facebook to NASA, and missions from cubesats to Orion are employing lasercomm to achieve gigabit communication speeds at mass and power requirements lower than that of traditional radio frequency (RF) methods.

Since first demonstrating free-space optical communications services with Lunar Laser Communications Demonstration (LLCD) in 2013, NASA has invested in developing optical communications technologies and capabilities to enhancing its space communications networks. Along with evolving optical space terminals, NASA is also developing lasercomm grounds stations capable of meeting the rapidly increasing data volume demands of upcoming missions, from low-earth to lunar orbits and beyond and integrating these advanced capabilities into its Near-Space and Deep Space Networks.

To meet this emerging need, the Low-Cost Optical Terminal (LCOT) project at NASA's Goddard Space Flight Center (GSFC) is designing, building and validating a prototype for a flexible, multi-mission, and economical optical ground terminal that could be used as a blueprint for a global network of optical ground stations, capable of supporting a wide variety of missions.

To date a major impediment to widespread adoption of laser communication has been the lack of an existing ground network infrastructure. A mission that wishes to take advantage of laser communication not only needs to invest in an optical space terminal, but it must also finance the creation of ground terminals to receive the downlink signal. This adds significant additional cost. Missions that do decide to incur the cost of financing a network of ground terminals end up building highly specialized optical receivers that are operable as receivers for that specific mission only. Significant Non-Recurring Engineering (NRE) cost is invested to build highly specialized one-of-a-kind ground terminals that go into storage after that particular mission is over. This is not an economical approach and does nothing to grow the number of optical ground stations available to future missions. In essence each mission that wants to take advantage of the benefits of lasercom has to start from scratch to provide a ground terminal network to support it. As long as this is the case, the cost for using laser communications will be too high for most missions to consider.

LCOT intends to close this gap in technology by designing and developing a standard optical ground terminal design that is flexible enough to serve as a receiver for a wide range of future missions – a ground terminal that can be quickly reconfigured to receive downlinks at different wavelengths using different signal formats. Not only does LCOT have the industry-building objectives of utilizing commercial-off-the-shelf (COTS) components to the maximum extent possible, but also spurs the commercial development of other necessary lasercomm components not currently offered by industry. Finally, LCOT will give NASA scientists and engineers a facility where they can gain real-world experience with optical communications. It will give engineers a cost-effective way to try out new concepts and processes by providing the infrastructure for such testing. In this way it is hoped LCOT will serve as a stimulus for innovation in optical communications and speed its widespread adoption by future missions.

The LCOT is comprised of five subsystems: Free-Space Optical, Transceiver, Amplifier, Monitor and Control, and Observatory Infrastructure. In August 2021, the LCOT team installed a 70 cm telescope, developed by Planewave Instruments that was optimized for optical communications. Free-Space Optical subsystem comprises of the telescope and its associated hardware, including a transmitter optical assembly, wide field cameras, two optical benches, and an adaptive optics subsystem. The transmit optical assembly, a unique concept design, is a cluster of four functionally independent transmit subassemblies located on the receive telescope. In addition to receiving optical signals and directing the expanded beam with high precision to the space terminal, it also performs tracking functions. The transmit

optical assembly will support operations from Low Earth Orbit (LEO) through lunar and will be used as a template for industry manufacturing. The Optical Infrastructure subsystem is responsible for providing environmentally controlled shelters for LCOT equipment and various other systems. To maintain the safety and proper functionality of the telescope, a 16 ft Astrohaven clamshell dome procured which provides all-sky coverage without the need to rotate the dome. Additionally, Atmospheric Monitoring Assembly (AMA) will be part of optical infrastructure subsystem to ensure accurate performance of the LCOT. Like existing optical ground stations, LCOT will measure standard weather station parameters, infrared all sky image of cloud cover, and cloud height. LCOT, however, adds requirements for measuring night time seeing and, in the future, daytime seeing.

Unlike other optical ground terminals, the LCOT is transceiver agnostic; user transceivers may be duplex transceivers, standalone receivers, or standalone transmitters with or without acquisition beacon functionality. As such, the LCOT project accommodates testing with external customer transceivers in a flexible manor, further complimenting its intended multi-mission goals.

Another unique component of LCOT is the use of a new amplifier technology – the Very Large Mode Area (VLMA) amplifiers. This new technology allows LCOT to avoid the issues faced by previous laser communications ground terminals, gives users more flexibility and modular capability, and is capable of reaching an order of magnitude higher peak power than traditional High Power Optical Amplifiers (HPOA). One drawback of the VLMA HPOA approach is that the amplified light is output into free-space. The solution developed by LCOT is an optics train that couples the output of the VLMA amplifier into a short fiber for transport to the transmit telescopes with high efficiency. Like many of the LCOT components, a set of detailed manufacturing drawings have been created for the optics train to allow any machine shop with a multi-axis Computer Numerical Control (CNC) machine to fabricate the piece parts from commonly available materials.

In line with the goals of LCOT, the monitor and control functions are developed as a modular and flexible system with the ability to support future hardware or algorithm changes, minimizing disruptions. A main priority of development in the Monitor and Control Subsystem (MCS) is the safety monitor system.

Keywords: laser communication, optical ground terminal, adaptive optics, Artemis

Acronyms/Abbreviations

ACCESS	Advanced Communications Capabilities for Exploration and Science Systems
ACME	Amplifier Monitor and Control Electronics
AMA	Atmospheric Monitoring Assembly
ANU	Australia National University
AO	Adaptive Optics
AS	Amplifier Subsystem
CNC	Computer Numerical Control
COTS	Commercial-off-the-shelf
FSOS	Free Space Optical Subsystem
GGAO	Goddard Geophysical and Astronomical Observatory
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HPOA	High Power Optical Amplifiers
IDD	Interface Definition Document
ILLUMA-T	Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal
LCOT	Low-Cost Optical Terminal
LEO	Low Earth Orbit
LLCD	Lunar Laser Communications Demonstration
MCS	Monitor and Control Subsystem
NRE	Non- Recurring Engineering
O2O	Orion Artemis II Optical Communications
OIS	Observatory Infrastructure Subsystem
POB	Port Optical Bench
PPM	Pulse-Position Modulations
RF	Radio Frequency
RFL	Raman Fiber Laser
Rx	Downlinks

SAA	Space Act Agreement
SCaN	Space Communications and Navigation
SOB	Starboard Optical Bench
TBIRD	Terabyte Infrared Delivery System
TS	Transceiver Subsystem
Tx	Uplinks
UPS	Uninterruptible Power Supply
VLMA	Very Large Mode Area
XOA	Transmit Optical Assembly

1. Introduction

The LCOT provides an accessible, powerful, and affordable multi-mission platform for optical communications, paving the way for NASA and industry to build more optical ground terminals in an efficient and cost-effective way. Optical communications services provide missions with higher data rates than comparable radio frequency systems. NASA is demonstrating the technology with multiple missions and integrating optical capabilities into existing space communications networks like the Near Space Network. Until now, NASA designed and built custom optical hardware or leveraged commercial components not intended for space applications and services. However, LCOT uses commercial off-the-shelf hardware when available or partners with industry to create commercial versions when not available, which reduces cost and expedites ground station implementation.

The LCOT effort is executed by Goddard Space Flight Center's Advanced Communications Capabilities for Exploration and Science Systems (ACCESS) Project as part of NASA Space Communications and Navigation (SCaN) program. Its driving objectives are to:

- Design an optical communication ground system architecture with the flexibility to support a range of use cases while leveraging industry capabilities to the maximum extent possible
- Create a prototype for a modular, repeatable, multi-mission optical ground station
- Establish the infrastructure for proving and demonstrating advanced optical communications technologies and capabilities
- Cultivate a range of commercial vendors to provide specialized optical communications components
- Conduct experiments with optical communications flight projects to demonstrate evolving LCOT capabilities
- Collaborate with universities and other research entities to advance optical communication capabilities

LCOT was designed to be a multi-mission optical ground terminal core and is not optimized for any specific, single mission. In the near term, the LCOT program is focused on developing its prototype station at the GSFC Goddard Geophysical and Astronomical Observatory (GGAO). By not being optimized for a particular mission, the optical performance for this prototype may be reduced when compared to a dedicated, mission-specific ground terminal, and may result in increased acquisition times and/or lower effective data rates. However, based on the knowledge gained from testing with this prototype, future terminals can be optimized, as needed. It is a primary goal of LCOT to be both affordable and repeatable and it is designed as such. LCOT prototype can be used as an experimental testbed for transceivers, adaptive optics, and other optical ground terminal technology. In the future, LCOT terminals can be easily adapted and integrated as an operational utility, assuming the availability of external ground communications channels.

In addition to the technical objectives described above, LCOT has also outlined several collaborative program objectives. LCOT has and will continue to cultivate a range of commercial vendors to provide specialized optical components. For example, ACCESS is working with Fibertek to develop COTS components for an optical communications transmitter. LCOT plans to conduct experiments with optical communications flight projects to demonstrate evolving capabilities. LCOT also collaborates with universities, such as Australian National University, the University of Arizona, and New Mexico State University, as well as other research entities to ensure that knowledge gained is shared across the optical communications community and the next generation in this new field is engaged[1].

2. LCOT System Overview

NASA's LCOT is located at the GGAO which is approximately 2 km away from the GSFC main campus and includes a direct fiber connection to GSFC, as shown in Figure 1. There are two main benefits to LCOT being in proximity to GSFC. First, it is an ideal location for experimenters (both local and visiting) and second, if technical changes requiring disassembly of the system are needed, the LCOT team can easily transport these parts to an optical

lab. This site at GGAO provides much of the infrastructure needed for future LCOT advancements. Additionally, this site is already used for outdoor laser transmissions, including satellite laser ranging work.

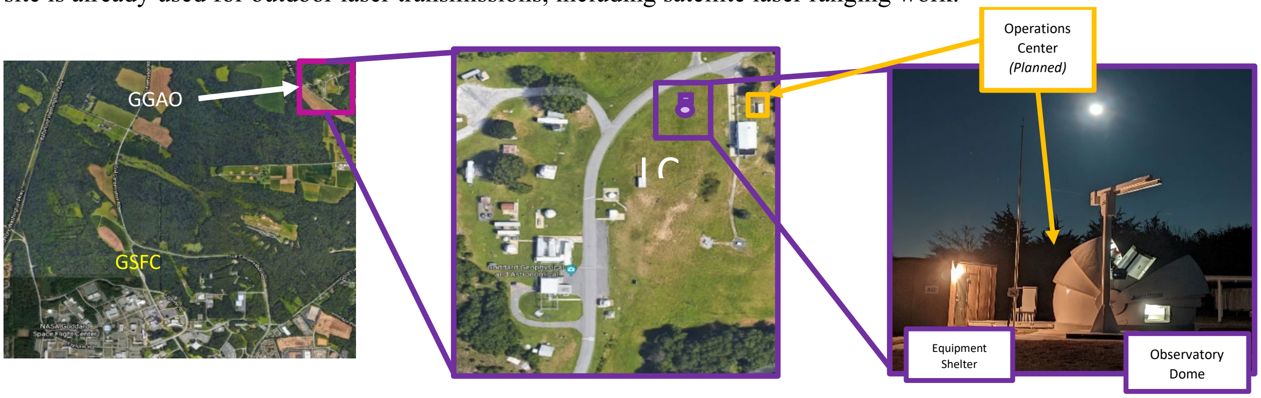

Figure 1. LCOT Facility Location

2.1 LCOT Architecture

The LCOT architecture is comprised of five subsystems: Free Space Optical Subsystem (FSOS), Amplifier Subsystem (AS), Monitor and Control Subsystem (MCS), Observatory Infrastructure Subsystem (OIS), and Transceiver Subsystem (TS). As shown in Figure 2, the MCS will send and receive control signals from each of the other four subsystems. Fiber optic connections will be used between FSOS, the TS, and the AS. Although its baseline architecture does not include an integral transceiver, LCOT can accept up to two transceivers at a time and transition between them during operations. LCOT is designed to accept a wide range of transceivers with little to no modification. Its modular design allows for easy configurations changes to be made when needed for more specialized transceivers [1].

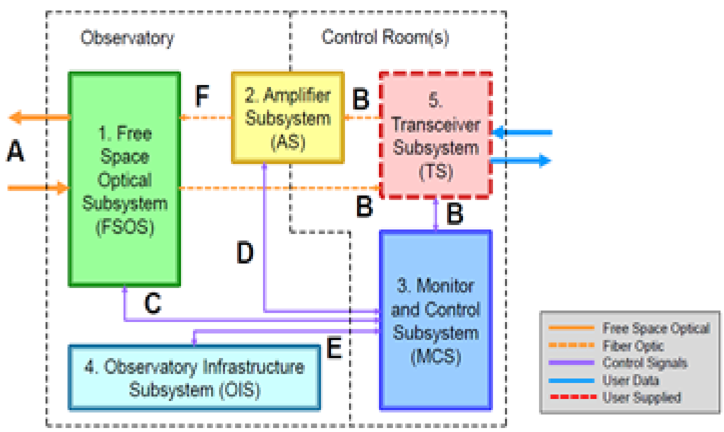

Figure 2. LCOT System Architecture

The functional purpose of the FSOS Subsystem is to provide a critical hardware interface between communications equipment confined to Earth's surface and similar equipment flying on active missions in space. As the term suggests, it must accept as input optical signals launched into free-space and process it such that its error-free transmission throughout large distances (include highly variable atmospheric conditions) is maximized. This basic function applies both to its ground terminal's high-power uplinks (Tx) as well as for low-power downlinks (Rx) from resident space assets operating from LEO to Lunar distances. [2]

To achieve these goals, the FSOS contains modular, interchangeable optics, electro-optics, and modems as well as a 70 cm receive aperture and custom gimbal for fast tracking and high stability with a large receive area. The configuration of the FSOS is made up of a transmit optical assembly (XOA), which is connected to the receive telescope by a robotic piggyback mount, the amplifier subsystem (AS) and two optical benches; the port optical bench (POB) contains adaptive optics (AO) for coherent downlink, while the starboard optical bench (SOB) supports direct detection missions like Orion Artemis II Optical Communications (O2O), as shown in Figure 3.

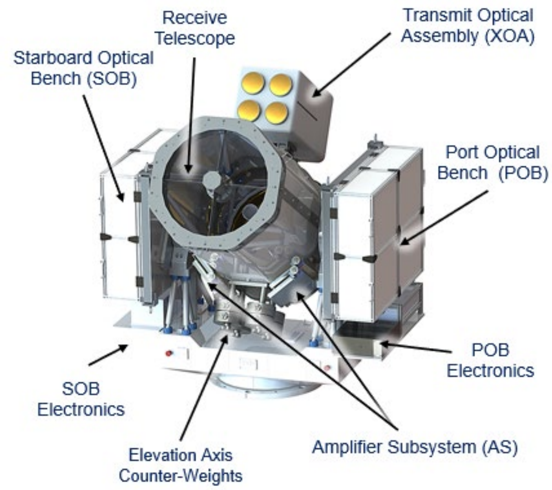

Figure 3. LCOT FSOS Rendering

The AS contains four VLMA HPOAs. These amplifiers allow us to avoid the issues faced by previous laser communications ground terminals and provide modular capability. The AS consists of three main components - the Raman Fiber Laser (RFL) pump, the VLMA amplifier head, and the optics train, as well as a safety system, the Amplifier Control and Monitor Electronics (ACME), used to prevent damage to the amplifier from loss of signal [1].

A key and driving requirement of LCOT is that it shall provide environmental protection of the FSOS and related components when not in use, which is the primary function of the OIS. As such, in the spring of 2019, a 16' Astrohaven Clamshell Dome was installed to protect the telescope and equipment located within. Additionally, the OIS is responsible for providing site power, managing the equipment shelter and future operations center, and housing the AMA.

The MCS is responsible for the overall monitor and control of the other LCOT components and provides a user interface for the operators and logging and reporting capabilities. The MCS includes the state machines, tracking, and backend opto-electronics for the POB, SOB and XOA. It interfaces with the AMA hardware for weather monitoring and analysis and monitors the status of other related OIS components, such as the Uninterruptible Power Supply (UPS) and the environmental controls. While the MCS is still early in its development and requires a significant amount of operator interaction to operate the LCOT at GGAO, the long-term goals are to reduce the need for operator intervention and enable remote monitor and control capabilities. A key goal of the MCS is to be as modular and flexible as possible. For example, if a future copy of the LCOT design includes a 1m diameter aperture rather than a 70cm aperture, minor adjustments and configurations updates would be required to the MCS software to accommodate that change.

The final LCOT subsystem is the TS. A key aspect of the LCOT prototype design is that it does not include a transceiver. The TS is the most complex subsystem of the LCOT and often needs to be mission specific. The other subsystems in LCOT were designed to be as flexible and modular as possible as well as mission-agnostic so that the only subsystem that might require significant non-recurring engineering at each deployment would be the TS. The LCOT effort is developing a TS Interface Definition Document (IDD) that describes what the users would need in their transceiver design to interface with remaining LCOT subsystems.

3. LCOT Planned Demonstrations, Capabilities, and Partnerships

The LCOT has several experiments planned with the Laser Communications Relay Demonstration (LCRD) to demonstrate and verify LCOT capabilities with an on-orbit optical communications mission. LCRD conveniently has a ground test modem located at GSFC and, using the existing fiber connection, can link to the LCOT's GGAO facility for each of these experiments. LCOT's capability verification with LCRD is broken into various phases based off the maturity of certain subsystems. Table 1 summarizes the phased testing planned with LCRD.

Table 1. Planned LCOT Experiments with LCRD

	LCRD Phase A	LCRD Phase B	LCRD Phase C	LCRD Full Demo
Description	Downlink with AO optical bench	Downlink with Non-AO optical bench utilizing automated WF/NF field-of-view tracking	Uplink and downlink using XOA and adaptive optics	LCOT and OGS-x optical relay via LCRD
Target Date	NET FY2023	NET FY2024	NET FY2025	NET FY2026
AO	✓	✗	✓	✓
Non-AO	✗	✓	✗	✗
Wide Field Tracking	Manual	Automated	Automated	Automated
Narrow Field Tracking	Manual	Automated	Automated	Automated
Temp Beacon & Temp XOA	✓	✓	✗	✗
XOA	✗	✗	✓	✓

The LCRD test is LCOT's first planned contact with an actual on-orbit laser communications downlink. This test is currently planned to be complete in FY2023. The operational XOA is currently in its design phase and is being worked in partnership with the University of Arizona. The final constructed XOA is expected to be complete in late FY2024/early FY2025. Therefore, in the initial tests with LCRD, LCOT will use only a transmit beacon signal via a temporary single aperture transmit telescope, allowing for LCRD to successfully transmit its downlink signal. The objectives of the early experiments are to characterize the LCOT prototype receive performance in the presence of actual atmospheric turbulence by measuring the power of downlink light coupled into a single mode fiber by the AO. In addition, LCOT will leverage the fiber connection and LCRD ground test modem located at GSFC to receive and transmit data and complete communications experiments.

Another major experiment that the LCOT effort is targeting is to communicate with the optical communications terminal flying on the Artemis II mission, named O2O. Artemis II is scheduled to launch currently in late 2024 and its optical terminal will be transmitting optical communications services at data rates up to 250Mbps.

The LCOT effort actively collaborates with external entities (e.g. other NASA centers, universities, industry) to identify the technology gaps in optical ground systems and figure out strategies for creating a commercial option in the future. There is an active collaboration ongoing with Fibertek to add a capability to generate the Pulse-Position Modulations (PPM) format for uplinking to missions such as the Artemis II mission. The LCOT effort is working closely with NASA-Glenn Research Center (GRC) to install receive superconducting nanowire detectors and modem that can receive the downlink from Artemis II [5]. NASA also has a Space Act Agreement (SAA) established with the Australian National University (ANU) to share expertise and performance data as they construct their own optical ground stations based on the LCOT design. The ACCESS Project is interested in exploring other opportunities to conduct experiments and tests with optical communication missions and collaborating with others on ways to enhances its capabilities and advance the optical communications field.

As a multi-mission ground terminal, LCOT can support missions ranging from LEO, like the Terabyte Infrared Delivery System (TBIRD) and Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T), out to Lunar distance for missions like O2O. Assuming a compatible ground transceiver is available, the LCOT's 70cm receive telescope can provide Lunar communications services on the order of 100s of Mbps. With its two optical benches, LCOT can be configured to support, for example, phase shift keying modulations (leveraging adaptive optics technology) and PPM services, enabling the LCOT system support both LCRD and O2O-like missions within a short time period. This flexible design for a multi-mission ground terminal is critical to implementing a global optical communications ground network. With this multi-mission design, the costs associated with NRE for future ground terminals will be significantly reduced. Additionally, the LCOT design can be adapted to support demonstrations and experiments with quantum communications. A standard design means if a mission procures a ground terminal for their specific purpose, then that ground terminal can be leveraged by other missions concurrently and in the future without expending significant NRE.

The LCOT prototype at the GGAO will be an effective test resources for NASA's and partner's optical communication technologies. It includes a weather station that monitors turbulence so that researcher can properly characterize the impact of atmospheric conditions on LCOT's performance. This data can also be used for selecting ground terminal site locations. Vendor modems can be tested with the LCOT with actual downlinks from spacecrafts. [1]

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